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Free-floating planets in stellar clusters?

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ABSTRACT
We have simulated encounters between planetary systems and single stars in various clustered environments. This allows us to estimate the fraction of systems liberated, the velocity distribution of the liberated planets, and the separation and eccentricity distributions of the surviving bound systems. Our results indicate that, for an initial distribution of orbits that is flat in log space and extends out to 50 au, 50 per cent of the available planets can be liberated in a globular cluster, 25 per cent in an open cluster, and less than 10 per cent in a young cluster. These fractions are reduced to 25, 12 and 2 per cent if the initial population extends only to 20 au. Furthermore, these free-floating planets can be retained for longer than a crossing time only in a massive globular cluster. It is therefore difficult to see how planets, which by definition form in a disc around a young star, could be subsequently liberated to form a significant population of free-floating substellar objects in a cluster.

Key words: stellar dynamics – planets and satellites: formation – stars: formation.

1 INTRODUCTION

The discovery of numerous extrasolar planetary systems in the solar neighbourhood (Mayor & Queloz 1995; Marcy 1999) has revolutionized our ideas of the planetary formation process and how it can vary from system to system. Specifically, the fact that most of the systems found contain relatively massive planets at small separations, in contrast to our Solar system, has engendered significant research into possible orbital migration (e.g. Lin, Bodenheimer & Richardson 1996). More recently, the discovery that there appear to be no such close systems in the globular cluster 47 Tuc implies a significant difference in planetary formation which could be due to the stellar environment (Brown et al. 2000; Gilliland et al. 2000). Indeed, it is possible that stellar interactions in the early stages of the globular cluster were able to disrupt the circumstellar discs before any planets were able to form (Bonnell et al. 2001), or that the increased radiation from the expected number of O stars was sufficient to remove these circumstellar discs before any planets could form (Armitage 2000). Encounters with passing stars in a dense stellar environment can lead to disruption of the planetary system and thus the ejection of the planets (see e.g. Sigurdsson 1992). This could lead to a population of free-floating planets in the cluster. Recently there has been a reported detection of a population of substellar objects in σ Orionis (Zapatero-Osorio et al. 2000) that could be due to stellar encounters. In this Letter, we investigate the formation of a population of free-floating planets in various cluster environments. We pay particular attention to the velocity distribution of this population, and the question of whether the bulk of the liberated objects could be retained in their natal environment once they are ejected from their parent system.

In the next section we discuss the properties of the initial planet population and of the various clusters. We then briefly summarize the issue of interaction cross-sections, including discussion of the different possibilities following an interaction. We then describe the simulations of the various encounters and derive velocity dispersions and other properties for both the free-floating and bound planet populations.

2 INITIAL CONDITIONS

Observations indicate that young stellar object (YSO) discs are typically 100 au in radius (McCaughrean & O'Dell 1996). Although it is not clear to what radius in the disc planets generally form, we can estimate based on our own Solar system that planet and planetesimal formation has occurred at radii out to 40–50 au. In contrast, the extrasolar planets found so far have been in orbits as tight as 4 d. These observations provide us with the plausible range of planetary orbits to investigate. The inner end of this range is unlikely to be strongly affected by encounters (Bonnell et al. 2001), although it is possible that, in sufficiently dense systems, stellar encounters are able to disrupt the planetary discs before the planets have formed or before they are able to migrate to these small separations. Furthermore, in the case of a young cluster the close orbits may not yet be populated as the migration time-scale is of the order of 10^7 yr or more (Lin et al. 1996). We therefore consider planetary orbits between 1 and 50 au

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Table 1. The properties of the types of clusters studied. The minimum and maximum impact parameters, b, are also shown. These correspond to roughly 10 and 99 per cent encounter probabilities for each cluster.

Cluster	Density pc^{-3}	V_{disp} $\mathrm{km\,s}^{-1}$	Lifetime yr	b (au) Min	Max
Globular	10^3	10	10^9	3.43	24.26
Open	10^2	1	10^9	33.32	221.22
Young	5×10^3	2	5×10^6	47.27	328.09

in radius. The initial orbits are all circular, and the distribution of separations is flat in log space. To restrict the parameter space studied, the parent and perturbing stars are assumed to be of equal mass, either 0.7 or 1.5 $\mathrm{M}_{\odot}$.

We consider three different cluster environments. The properties of these are summarized in Table 1. Our cluster environments are intended to correspond to a globular cluster (dense and long-lived, with a high velocity dispersion), an open cluster (more diffuse with a much lower velocity dispersion), and a young cluster [intended to correspond to conditions in dense star-forming regions such as the Trapezium: see e.g. Clarke, Bonnell & Hillenbrand (2000)]. The impact parameters are drawn from the expected probability distribution for the cluster environment. This is calculated using the mean time between encounters given by Binney & Tremaine (1987),

$$\frac{1}{t_{\mathrm{enc}}} = 16\sqrt{\pi}nv_{\mathrm{disp}}R_{\mathrm{enc}}^2\left(1+\frac{GM*}{2v_{\mathrm{disp}}^2R_{\mathrm{enc}}}\right). \quad (1)$$

Here, t_{enc} is the mean time between encounters within a distance R_{enc}, n is the number density of stars in the cluster, and v_{disp} is the velocity dispersion.

3 SIMULATIONS

Simulations of restricted three body motion were carried out using a 4th order Runge–Kutta code with adaptive step-size on the ETH's Asgard cluster.[1] The Runge–Kutta code was found to conserve energy over the interactions to a few parts in 10^5 or better. Initial planetary orbits were selected at random from the log-flat distribution. The planetary orbits were isotropically distributed with respect to the stellar orbit. The stellar orbit was started at a point where the potential energy of the stellar system was 1 per cent or less of the kinetic energy. The planets were not inserted into the simulation immediately, but only when the ratio of the force from the perturber to the force from the parent reached 0.01 for one of them. This was done to speed up the simulation during the long approach of the perturber. Trial simulations showed that the difference caused by inserting the planets at this stage was negligible.

4 RESULTS

Table 2 shows the number of planets that became unbound, remained bound to the parent star, or were exchanged during the simulation. As expected, a substantial number of planets were unbound in the dense, long-lived globular cluster environment, fewer in the open cluster case, and fewer than 10 per cent in the young cluster case. More disruption occurred for the high-mass stars than for the lower mass case.

[1] Asgard is an Intel Pentium III Beowulf cluster located at the Eidgenössische Technische Hochschule in Zürich. It comprises 502 CPUs on 251 Dual-CPU nodes.

Table 2. The fate of planets in different cluster environments. In the case of ionization, three fractions are shown: the total percentage of systems ionized, the percentage that are retained in the cluster, and the percentage that escape within a crossing time.

Cluster	Ionized (per cent) Total	Kept	Lost	Survived (per cent)	Exchanged (per cent)
Globular	47.3	30.1	17.2	51.5	1.3
Open	26.6	0.5	26.1	61.1	12.3
Young	7.8	0.5	7.3	90.1	2.1

4.1 Velocity distributions of free-floating planets

For the planets that became unbound, the velocity at infinity was estimated from the total energy (kinetic plus potential) of the planet and, assuming this energy is conserved while the planet escapes from the gravitational potential, then $(1/2)mv^2 = E_{\mathrm{tot}} \geq 0$. The simulations with high-mass stars produced more high-velocity liberated objects, but the difference in the final velocity distributions was not large.

Graphs of the velocity distributions in various clusters are shown (Fig. 1). The distributions are normalized to the total number of planets. It is interesting to compare the distributions with the estimated escape velocity for the cluster (vertical line). It is apparent that, whilst the globular cluster will retain the bulk of its free-floating planets, most liberated planets in the young cluster or open cluster will tend to escape within a crossing time. In Table 2, the fraction of planets liberated in each cluster has been broken down according to whether the planet subsequently escapes the cluster or not.

We note here that a change in the assumed outer edge of the planetary orbit distribution, for example truncating the outer orbital radius closer in, would of course lead to a modification of the final velocity distribution. The more distant objects are more prone to disruption, but this is offset by their being less numerous owing to the flat-log initial distribution of orbits. Truncating the initial orbits at 20 au rather than 50 au would reduce the fraction of liberated objects to around 50 per cent for the globular cluster, 25 per cent for the open cluster or around 2 per cent for the young cluster. This reduction would also tend to affect the low-velocity population more than the high-velocity tail, since the high-velocity objects come predominantly from the inner orbits.

Also shown in Fig. 1 are fits to the distributions. The globular cluster case is reasonably well fitted with a Gaussian. The other two distributions do not resemble Gaussians, and can only be poorly represented by a Maxwellian. The distributions shown in these cases were constructed by taking the product of the initial planetary orbital velocity distribution (including the stellar velocity dispersion), and the observed cross-section as a function of initial velocity, and then convolving with a Gaussian. The amplitude of the distribution and the sigma for the Gaussian were then left as free parameters in the fit. These distributions do not represent the observed distribution entirely satisfactorily (they do not reproduce the high-velocity tail), but they serve to illustrate the essential difference between the high-velocity globular cluster case and the low-velocity clusters. In the high velocity dispersion environment of the globular cluster, the emerging planetary velocity dispersion is dominated by the stellar scattering, whereas

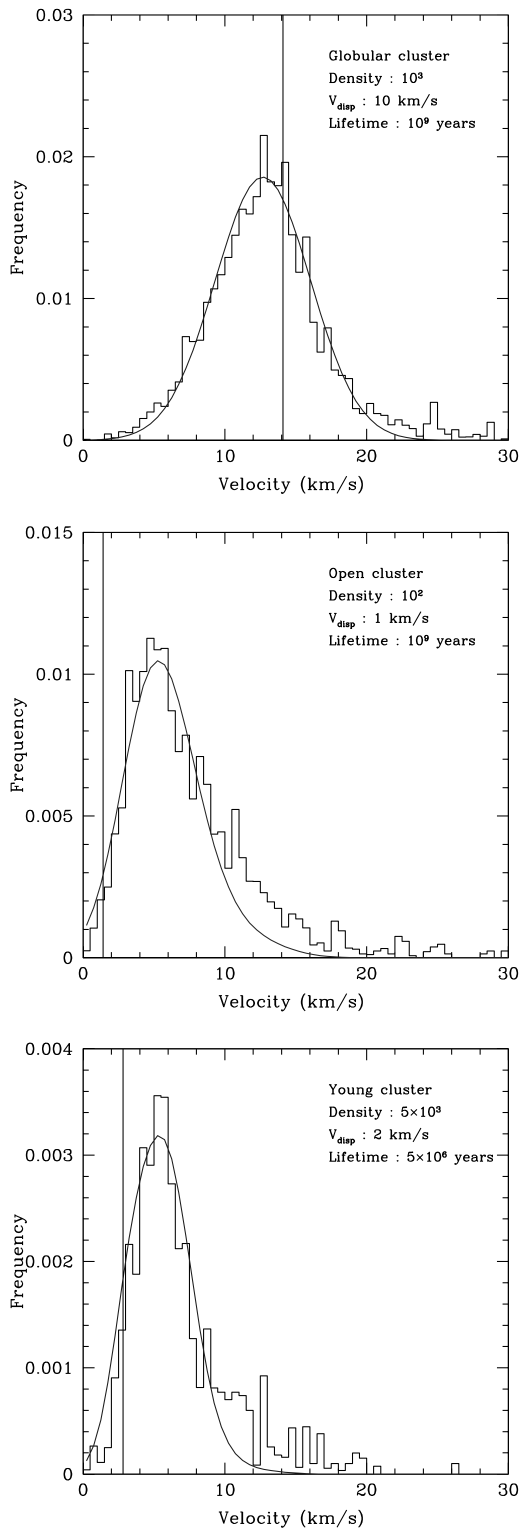

Figure 1. The velocity distributions for the populations of free-floating planets in each of the three cluster environments. The histogram is the distribution of total velocities. The vertical line in each case shows the estimated cluster escape velocity. In each case, a fit to the velocity distribution has been made. The globular cluster case is fitted with a Gaussian and the other two cases are fitted with a function derived from the initial velocity distribution of the ionized systems. See text for details.

in the open cluster or young cluster environment the ionized planetary population retains a memory of the initial Keplerian orbital velocity distribution. It is this effect that leads to the liberated population escaping from the low velocity dispersion clusters.

4.2 The effect of varying planetary masses

We tested the effects of the restricted three-body assumption for some specific cases using a three-body Runge–Kutta code and various planetary masses. It was found that, for systems where the planets were retained by the parent star, the final binding energies differed by at most a few per cent between the massless planet case and the three-body code with a mass of $0.001\,M_\odot$ (i.e. 1 Jupiter mass). We also examined cases where the planetary system was ionized, and investigated to what extent changing the planetary mass affected the final escape velocity. The effect was found to be usually modest for the range of masses applicable to planets (1 to 10 Jupiters), but could be critical in certain circumstances. The escape velocity usually decreased as the planet mass was increased, although there were cases where the opposite occurred. Several cases were found where modest changes of planetary mass produced critical changes in the escape velocity or changed the encounter outcome from ionized to retained or exchanged. These were all distant interactions, in which the closest approach of the perturbing star to the parent star was greater than the initial planetary orbit. In these cases, ionization is of course sensitive to the encounter conditions, and only a minority of systems in these encounters were ionized. We therefore conclude that the velocity distributions presented would not be changed dramatically for any realistic population of planets (up to $10\,M_{Jup}$).

4.3 The bound population: separation and eccentricity distributions

In Fig. 2 we show the distributions of separation and eccentricity for the planets that survive encounters. Separate distributions are shown for the cases where objects are retained by the parent star and where they are exchanged. As might be expected, the planets retained by the parent tend to lie in close orbits. The planets captured by the interloper occupy a flatter separation distribution. A similar trend is seen in eccentricity. The retained planets have nearly circular orbits; the exchanged ones have a flat eccentricity distribution. The highly eccentric systems and captured systems with large separations will of course be much more vulnerable to disruption in subsequent encounters. The effects of scattering on the population of bound planetary populations in open clusters were investigated in some depth by Laughlin & Adams (1998).

5 CONCLUSIONS

We have investigated how a population of free-floating planets can be generated by stellar encounters in different cluster environments. We have found that in globular clusters a relatively high fraction of any planetary population is likely to be liberated by encounters over the cluster lifetime, and furthermore that the majority of these systems should be retained in the cluster at least until they are lost through two-body relaxation after several thousand crossing times.

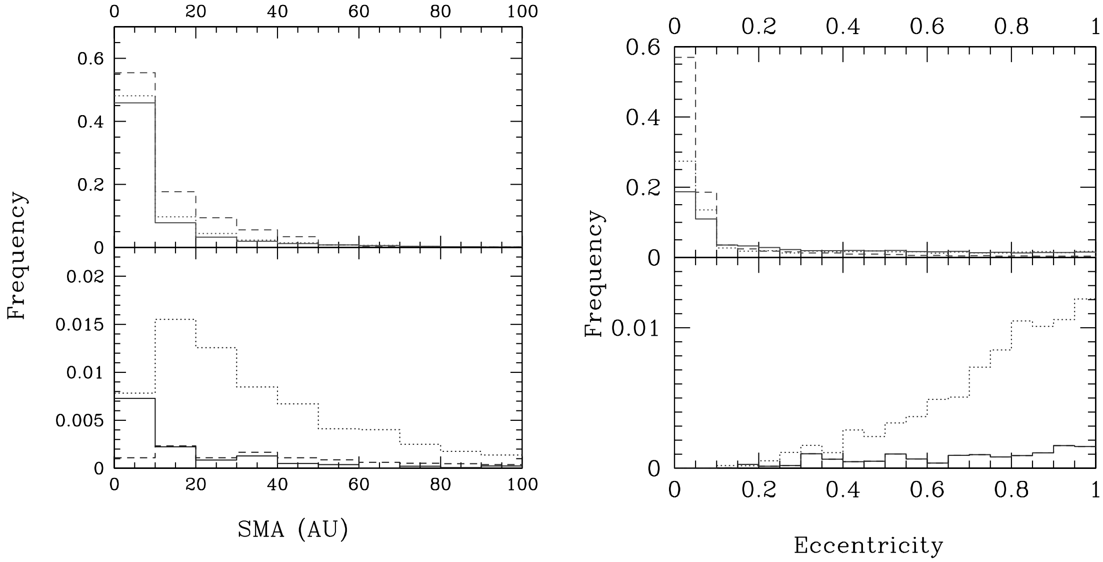

Figure 2. Distributions of semimajor axis (left) and eccentricity (right) for surviving planetary systems. Top panel: systems retained in an encounter; bottom panel: systems exchanged. The solid line shows the globular cluster case, the dotted line denotes the open cluster case, and the dashed line gives the young cluster case. The frequency has been normalized to the total number of systems.

In the less dense environments of an open cluster or young star-forming cluster, planet liberation was found to be less efficient, although still capable of producing a significant population of free-floating planets. However, it was found that these objects were liberated at too high a velocity to remain bound in the cluster. In each case, only a fraction of a per cent of the planetary population was liberated but remained bound to the cluster. This suggests that there should not be substantial numbers of free-floating planets in such environments. Furthermore, any such objects that were observed in stellar clusters would be expected to have a higher velocity than the cluster stars, and so to be found predominantly in the outer regions far from the cluster core.

This has a bearing on the recent discovery of substellar objects in σ Orionis (Zapatero-Osorio et al. 2000). The objects found in this study were typically many Jupiter masses, although some were as little as 5 M_{Jup}. It is not clear whether such massive objects should better be regarded as planets or as brown dwarfs. Our results imply that they have probably formed independently rather than in a protostellar disc. The higher mass of some of the σ Orionis objects (up to $50\,M_{Jup}$) should not strongly affect the escape velocities except in the a few cases of distant encounters (see Section 4.2).

We note finally that the objects escaping from stellar clusters will form a population of fast-moving unbound planets in the Galactic disc. However, this would not be expected to form a significant contribution to the total mass of the Galaxy.

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